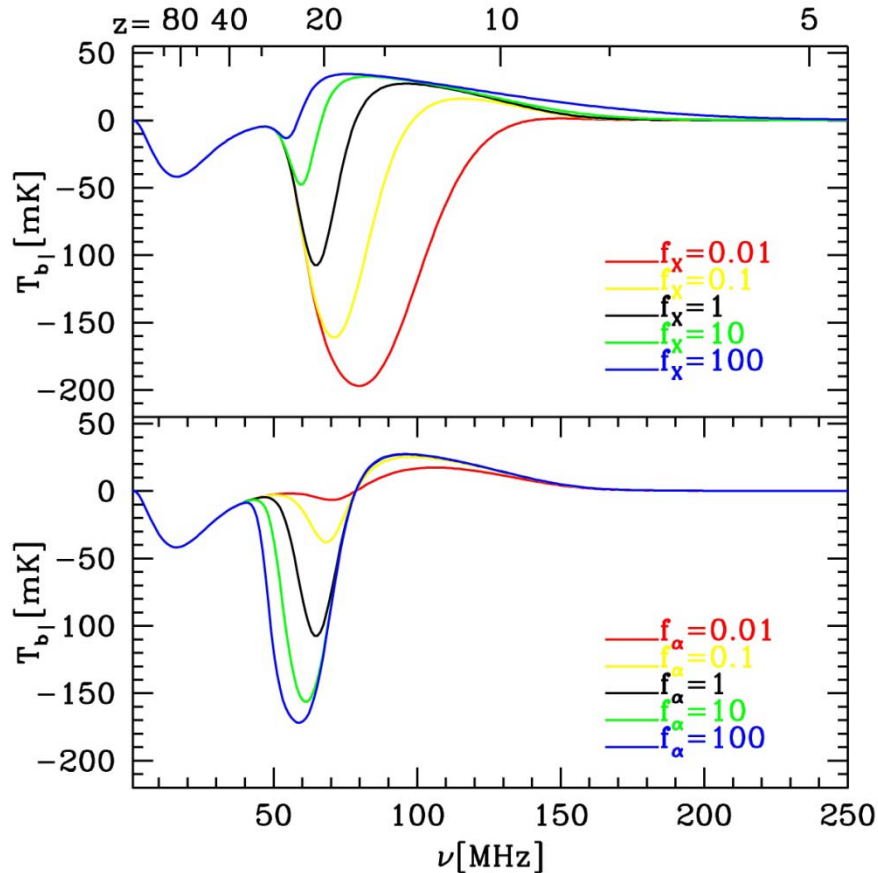# Extracting information about high-redshift cosmology from a lunar-orbiting dipole

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# The global high-redshift 21-cm signal

Pritchard & Loeb (2010)

- Dark ages (z≈60) insensitive to most astrophysical parameters, but probes cosmology and exotic physics.

- 'Cosmic twilight' (z≈15-30) sensitive to properties of first sources.

- Epoch of reionization (z<15) to be probed in the near future through interferometric experiments.

The sky at 150 MHz

de Oliveira-Costa at al. (2008), 150 MHz


2.3 ... 3.7

$\log_{10}(T/K)$
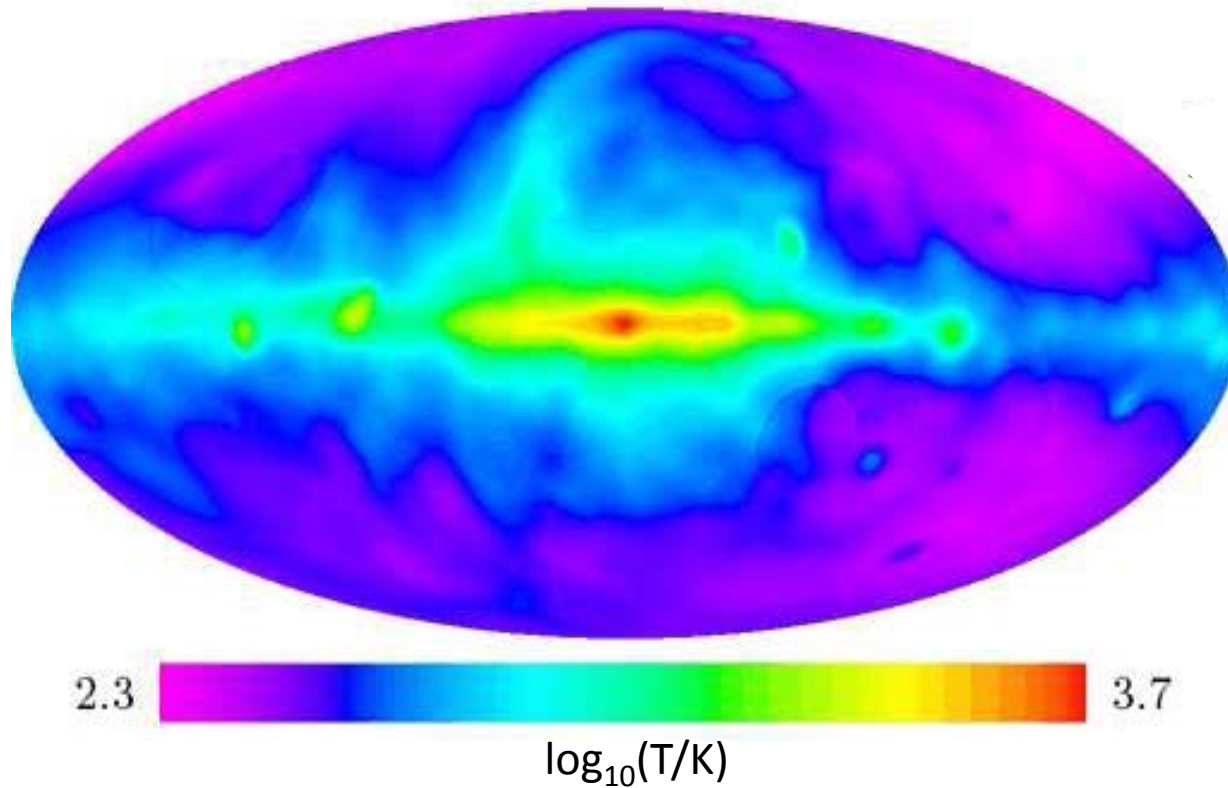
# Magnitude of foreground subtraction problem
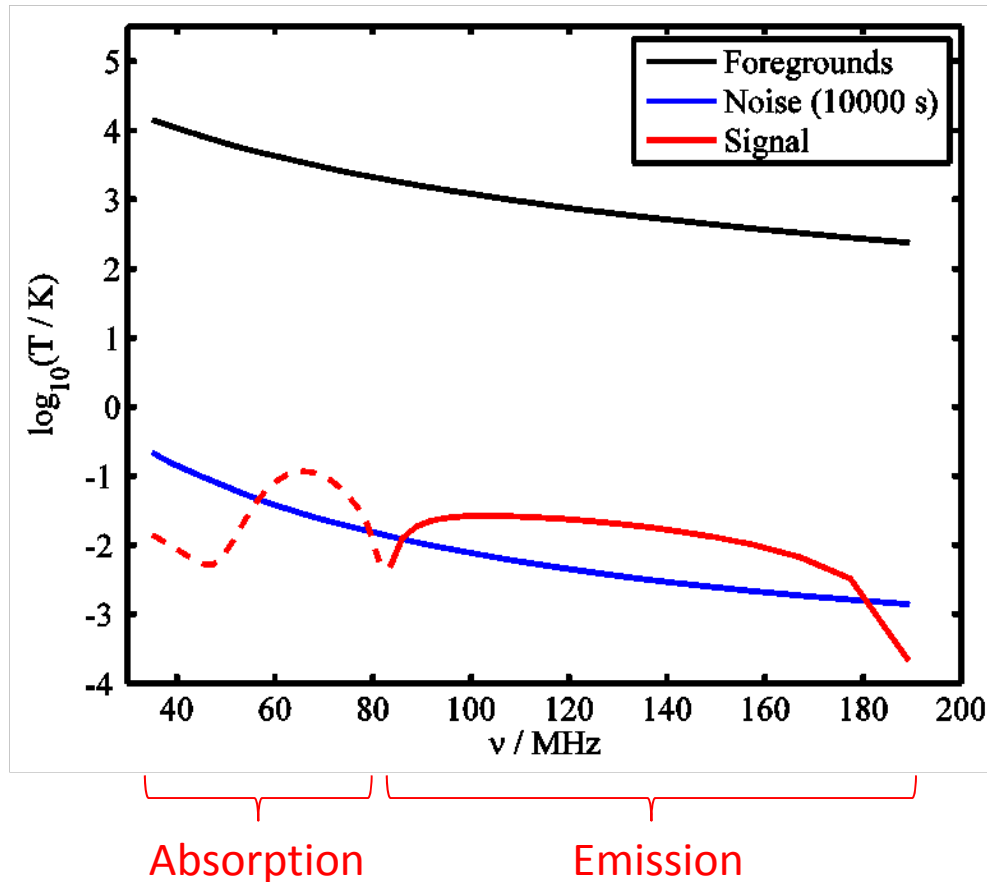
- Even after only 10000 seconds, the thermal noise may be comparable to the signal.

- Unfortunately, both are four or five orders of magnitude below the level of the foregrounds!

- Both the foreground subtraction and the instrumental calibration must be extremely accurate.

# Foreground subtraction in an ideal case: epoch of reionization (EoR)
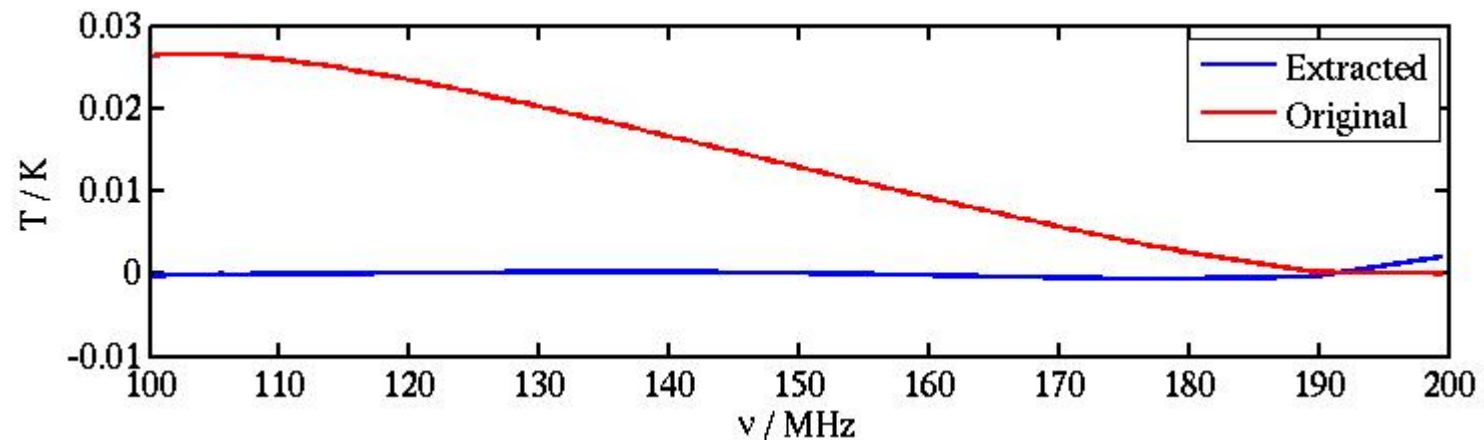
- Look at high frequencies, during the EoR.
- Model foregrounds as a perfect power law
- Assume zero noise
- Fit a power law to the spectrum and subtract it
- No trace of the EoR signal remains!

Foreground subtraction in an ideal case: extending to low frequency
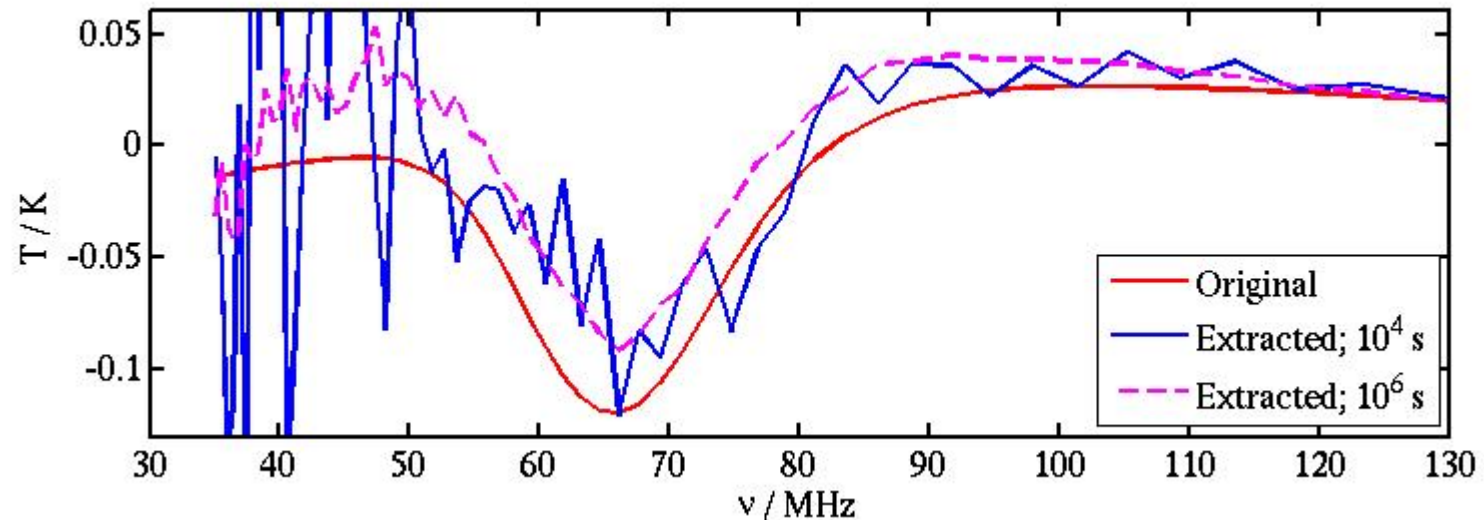
- The Lyman alpha coupling dip at around 65MHz is much easier to extract than the smooth EoR feature.
- Modest integration times allow us to find e.g. the position, width and depth of the dip.
- It also provides an anchor which may allow us to find the peak of the emission and thus constrain the EoR better than missions focused solely on EoR frequencies.

Constraints on model parameters (500 hours of observation)
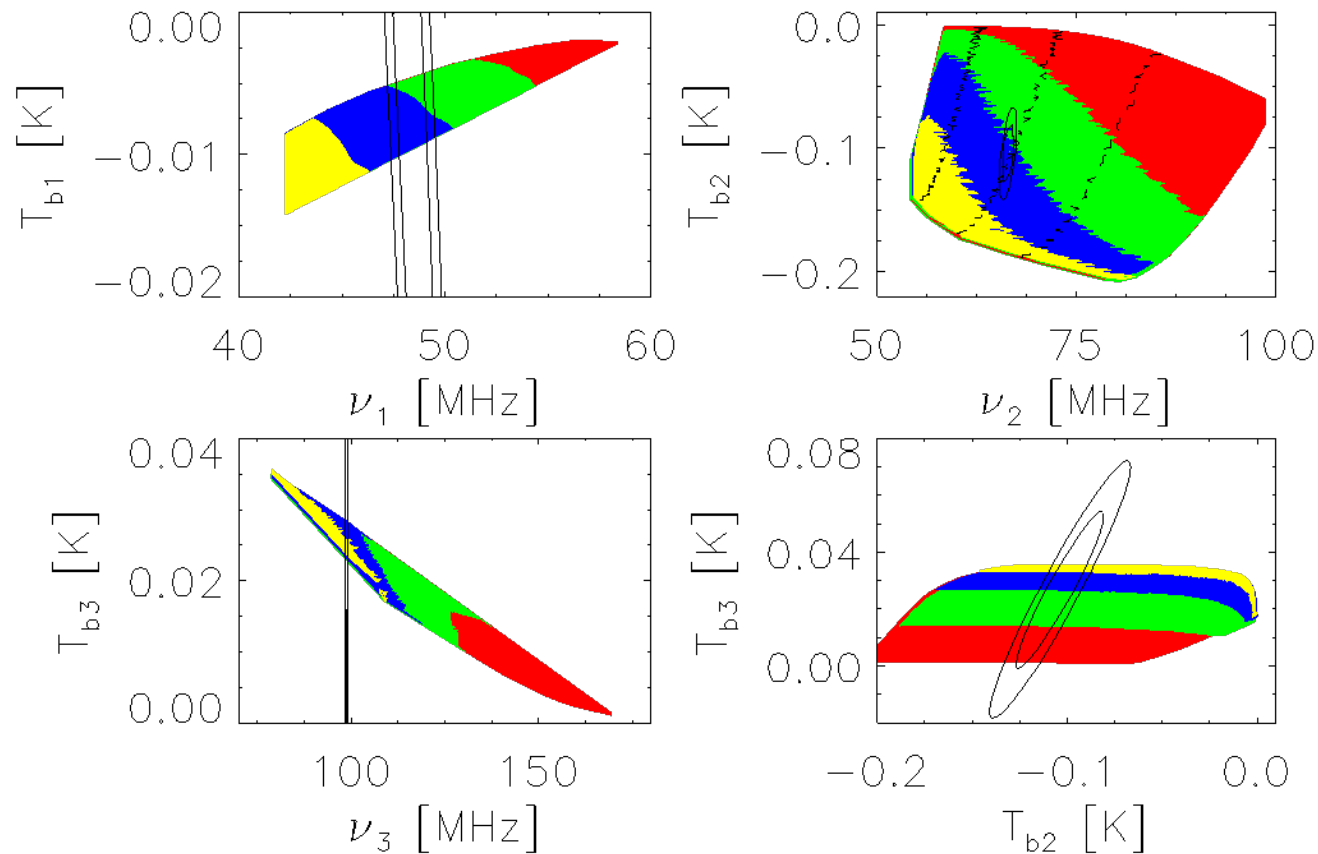

Pritchard & Loeb (2010)

Foreground subtraction in more realistic cases

- We cannot expect that the real foregrounds will follow a simple parametrized form.
- We can either hope that the foregrounds can be closely approximated by a parametrized form with relatively few degrees of freedom, else use non-parametric methods to fit them.
- A non-parametric method which seems to work for interferometric observations is Wp smoothing
  - Can enforce the condition that the foregrounds contain no inflection points ('wiggles').
  - Minimizes the integrated change of curvature (enforces smoothness).
  - There are questions as to whether such a method really has sufficient dynamic range to fit realistic foregrounds.

Using time-ordered measurements

- A spectrum as a function of time provides more information than an integrated spectrum:
  - Foregrounds have different intensities, and possibly different shapes, in different parts of the sky.
  - A dipole averages over a sufficiently large area that the signal is unchanged for different parts of the sky.
- Can infer the covariance matrix of the foregrounds and construct a matched filter for a proposed signal.
- Statistical techniques such as independent component analysis can be used to separate out the foreground and signal components.

Matched filter approach: very preliminary!
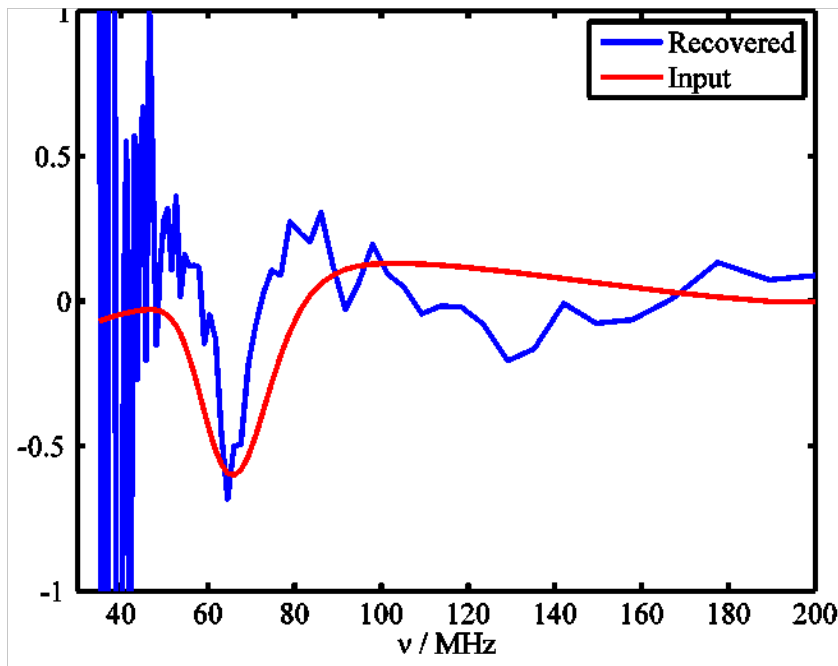
- Treat the time-varying foregrounds as pseudo-stochastic noise.
- Add thermal noise appropriate for 24000s of observation.
- Construct a matched filter using the computed covariance matrix of the foregrounds and noise.
- This first attempt seems to recover the position of the 'cosmic twilight' absorption trough.

Independent component analysis: a blind source separation technique
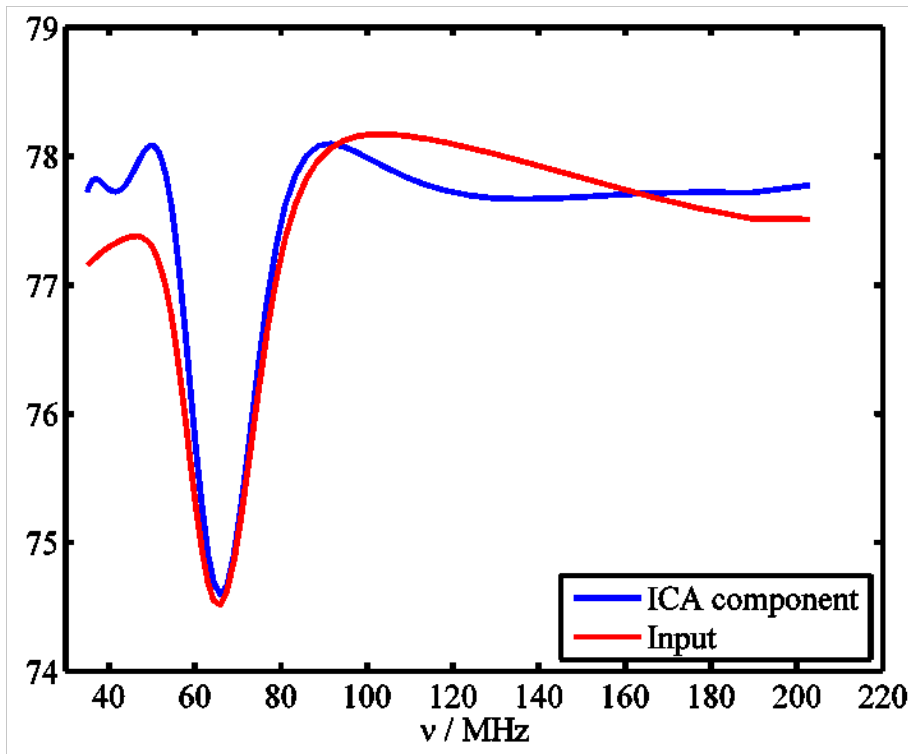
- ICA appears to be able to capture the width and position of the absorption trough well, but…
- Hard to identify the component corresponding to the signal automatically;
- Normalization of all components is lost.
- Descriptions of the technique in the statistics literature often ignore noise!

Bandpass calibration

- Unless we understand the antenna bandpass very well, we must fit the foregrounds and the bandpass simultaneously.

- EDGES uses a 13th order polynomial for this purpose, destroying information about small-scale structure in the signal.

- An external calibration source would allow us to take out the bandpass without fitting.

- A lunar-orbiting dipole has the unique opportunity of using the Moon as a calibration source.

The Moon as a calibrator

- A spinning satellite could alternate between pointing at the Moon and pointing at the sky.
- Would be sensitive to the temperature of the Moon at distances of order a wavelength below the surface.
- At low frequencies, this is deep enough that the temperature is relatively stable.
- Requires further modelling and investigation of whether the Moon is stable enough and can be treated as a black-body radiator at low frequencies.

Conclusions

- For the next few years, global 21-cm measurements are the only way to constrain the cosmic dark ages and twilight.
- This also provides complementary information on reionization to interferometric experiments.
- Noise can quickly be reduced to a level where we can obtain serious constraints on model parameters, but…
- …foregrounds are the major problem.
- Several promising methods use frequency and spatial structure of the foregrounds to get at the signal, though further study is required.
- Antenna calibration is a major hurdle, which may be overcome by using the Moon as a calibration source.